Ultraviolet and Visible-light Coronal Imager for the Solar Orbiter

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1 Introduction

The payload concept for the Solar Orbiter (SO) Mission to the Sun and Inner Heliosphere includes a full-corona imager. The Ultraviolet and Visible-light Coronal Imager (UVCI) for SO is a coronagraph for the observation of the radiative emission from the most abundant elements in corona: hydrogen and helium. UVCI will simultaneously measure the UV emission and the polarized brightness (pB) of K-corona images. The primary and novel scientific objective of this instrument is the determination of H and He flow speeds and abundances and the electron density in corona, at helio-centric heights comprised between 1.2 and 3.5 solar radii ($R_\odot$), when the SO distance from the Sun is 0.21 A.U. during the nominal mission. During the extended mission, when the SO moves to 0.36 AU, the UVCI field-of-view extends up to the $(2-6)$ $R_\odot$ range. The instrument is an externally occulted coronagraph. The coronal imager encompasses an extreme ultraviolet (EUV) channel for the observation of the Lyman-α emission of H^0 (H I λ 1216 Å) and He^+ (He II λ 304 Å), and a broad-band visible light channel for the measurement of the polarized brightness (pB) of the K-corona. The H^0 and He^+ Lyman-α images are separated with narrow-band transmission filters.

2 Science Goals

Hydrogen and Helium are the most abundant coronal elements. The proposed UVCI for the Solar Orbiter is designed to take images of the neutral hydrogen and of the single-ionized helium at helio-centric heights comprised between 1.2 and 3.5 solar radii ($R_\odot$). UVCI will also determine the coronal electron density. The Visible and EUV corona will be imaged with UVCI for the first time from an out-of-ecliptic vantage point, allowing a unique view of the plasma distribution and solar wind expansion in the coronal low–latitude/equatorial belt. UVCI will exploit the helio-synchronous orbit of SO by following for several days the temporal evolution of coronal structures (e.g., streamers, coronal mass ejections) without the confusing changes of prospective introduced by the solar rotation.

Scientific rationale: The primary scientific objective of these observations is the determination of H and He flow speeds and abundances in corona and their evolution. This goal includes and extends the science pioneered by the Ultraviolet Coronagraph Spectrometer (UVCS) of the SOHO mission. UVCS/SOHO has obtained the first coronal images of the H I Lyman-α (H I Lyα, λ 1216 Å) emission, althogh in limited field-of-views (FOV). UVCI includes the H I Lyα imaging capability of UVCS, and extends it - for the first time - to the He II Lyα, λ 304 Å. This will allow the first determination of the absolute abundance (i.e., relative to hydrogen) of helium in corona.

He abundances: Helium is the second largest contributor to the density of coronal plasma, making it potentially important for the dynamics of solar wind. Indeed, helium may act as a regulator to mantain a nearly constant solar wind mass flux. Particle flux measurements at 1 AU show variable helium abundance over the range 1% to 15% of hydrogen, with typical values of 5% (quite constant) in high speed flows and of 2% (highly variable) in the slow solar wind. Helium generally flows faster than hydrogen by the absolut Alfvén speed. The overall low abundance of helium is most easily attributed to its high First Ionization Potential (FIP), suggesting fractionation in the chromosphere, but the abundance variability is an open question.

Fast solar wind: The He II Lyα, λ 304 Å, is by far the brightest helium line in the corona. Like H I Lyα, this line is formed largely ($> 90\%$) by resonant scattering of the chromospheric emission line, so the methods, such as the Doppler dimmimg technique, developed to analyze UVCS/SOHO observations of H I Lyα can be applied to the He II Lyα. UVCI includes a broad-band visible light channel for the measurement of the polarized brightness (pB) of the K-corona. The combination of the Doppler dimming profile and electron density from the pB measurements will provide the helium flow speed in the solar wind.

Slow solar wind: UVCS data have shown a striking difference between the core and the edges of quiescent equatorial streamers. While the streamers are brightest along the axis in the H I Lyα, they are strongly edge-brightened in the O VI, $\lambda\lambda$ 1032/1037 Å, due to a strong gradient in the oxygen abundance. The strong depletion of oxygen five-times ionized in the closed-field cores of streamers can be explained by gravitational settling of the heavier ions in hydrostatic enviroment. The bordering edges of the streamers show the FIP abundance enhancement seen in the slow solar wind, while the abundances in the streamer core are 3 times lower. Observations of the abundance morphology of helium (A=4), via the He II emission line, can fill in the current observational gap between low-mass (A=1) protons and high-mass (A=16) oxygen ion to test the gravitational settling hypothesis. UVCI will be able to observe the same structure on the plane of the sky during the corotation periods and therefore to study the variations due to gravitational settling within the streamers.

Coronal mass ejections: UVCI has full-corona imaging capabilities. This is different from UVCS/SOHO, whose field of view is limited by the spectrometer slit. This capability of UVCI can be used for the study of the morphology and dynamics of coronal mass ejections (CME). The different sensitivities to the Doppler dimming of the H I and He II Lyα lines (120 km/s and 80 km/s, respectively) will provide a valuable diagnostics of the CMEs' outflow velocities.

3 Instrument Concept

UVCI is an externally occulted telescope designed for narrow-band imaging of the EUV corona in the He II 304 Å and H I 1216 Å lines, and for broad-band polarization imaging of the visible K-corona. The telescope optical configuration is a two-reflection Gregorian. The EUV Lyα lines are separated with EUV trasmission filters. The visible light channel includes an achromatic polarimeter, based on electro-optically modulated liquid crystals.

3.1 Optical Design

Telescope: The external occulter ensures both thermal protection for the optics and better stray-light rejection. The Gregorian telescope design has been chosen because it gives real images of the external occulter and the edges of the telescope primary mirror. In this way, these sources of stray-light can be easily blocked with stops. A light trap behind the primary mirror ensures that only the light reflected by the mirror enters the Filters/Detectors Assembly structure. The direct light from the solar disk is mostly dumped into space, and part of it might be used for radiometry and coarse imaging of the solar disk in the three wavelength bandpasses.

UV and Visible-Light Channels: The instrument structure is made of carbon fiber, with Zerodur optical components. Zerodur is used for the mirrors' substrate because of its extremely small thermal expansion coefficient. Optics made with this material is also easy to polish into non-spherical figures with sub-angstrom rms surface roughnesses.

The basic specifications and drivers of the instrument are summarized in Table 1.

Telescope	Gregorian type;
Occultation	External occulter; 500 mm diam.
Optics Field of View	2 mirrors: Zerodur substrate Annular, Sun-centered. Coverage: 1.2 – 3.5 $R_\odot$ at 0.21 A.U. (Nominal mission) 2.0 – 6.0 $R_\odot$ at 0.36 A.U. (Extended mission)
Spatial Resolution (SO at 0.21 A.U.)	880 Km (6 arcsec) 5,880 Km (40 arcsec at 3.5 $R_\odot$)
Stray-light	$< 10^{-8}$ (Visible light); $< 10^{-7}$ (304, 1216 Å)
Wavel. Bandpasses Detectors	1) He II λ (304 $\pm$ 20) Å 3) Visible λ (4500 – 6000) Å (H I and He II are detected simultaneously) 1 for Visible-light, and for 1 for EUV (304, 1216 Å); Active Pixel Sensor (APS) or Charge Injection Device (CID) (EUV intensified); Radiation hardening > 50 KiloRad Si total dosage; 4096 $\times$ 4096 array – 15 μm pixels;
Data Rate	0.08 Mbps (each detector; lossless compression) (SO Spectrometer package in perihelion: 0.063 Mbps)
Lossy Compr. Factor	7 – 10 $\sim$ (UVCI data acc.)/(SO data acc./4 opt. instr.)
Data Volume	$\sim$ 1 Gbit/day (lossless compression)
Data Accumulation (1 perihel. passage)	$\sim$ 26 Gbit per orbit (SO Spectr. package data acc. in perihelion: 140 Gbit)
Phys. Dimensions	(80 $\times$ 30 $\times$ 30) cm^3
Mass (kg) Power (W)	22 – Total. 4 – shielding if required 35 (Operational mode, peak); 25 (Stand-by mode)

Table 1: Summary of the UVCI specifications

3.2 Thermal

The occulter is the element of the coronograph which achieves the highest temperature since it is directly exposed to the Sun when the Solar Orbiter is closer to it (contrarily to the cover) and has an exiguous conductive link (represented by the thin rods of the support) with the rest of the structure.

The temperature achieved by the occulter has been assessed by assuming a purely radiative heat transfer and a coating made of white paint of the same type of that utilised for the sunshield of the Payload Module. For this white paint the following thermo-optical parameters are given (ref.: Solar Orbiter Pre-Assessment Study, pag. 61).

The thermal flux incident on the occulter is 31 kW/m^2 at 0.21 AU and 5.5 kW/m^2 at

0.5 AU. The extremes of the temperature experienced by the occulter along the observation arc [i.e., $\Delta T = T(0.21 AU) - T(0.5\ AU)$] have been computed for the thermo-optical coefficients (α) at beginning of life (BOL) and end of life (EOL). The results are:

$$\begin{aligned} \Delta T(\alpha = 0.20) &= 217.6\ °\mathrm{C} \\ \Delta T(\alpha = 0.45) &= 266.5\ °\mathrm{C} \end{aligned}$$

Considering that the value of α along the first operational orbit will be between α(BOL) and α(EOL), the occulter temperature will be in turn between the values corresponding to BOL and EOL. A further small reduction of the temperature will be caused by the transport of part of the heat through the occulter supports.

3.3 Detectors

There are two detectors, optimized for the Visible $\lambda\lambda$ (4500 – 6000) Å) and the Extreme-UV (304, 1216 Å). The baseline detectors are Active Pixel Sensors (APS). This detector system looks particularly attractive for a possible high radiation dose environment, like that at 0.4 AU from the Sun. It is also being investigated the possibility of using Charged Injection Devices (CID). This detection system is highly resistant to space radiation. It can easily withstand more than 100 times the lethal dose of CCDs. Custom CID can be used for radiation hardened systems greater than 1 MegaRad Si total dosage. (CIDs were developed for monitoring underground nuclear tests!). This intrinsic resistance of the CIDs to high doses of radiation would result in a weight saving for the shielding.

CIDs have random-access pixels (i.e. it is possible to choose which pixel has to be read individually). The capability of random pixel address permits dynamically programmable read-out of individual pixels and sub-arrays: this can be useful in UVCI for limiting the readout area to the solar corona

The area array has (4096 × 4096) 15-μm pixels. For the EUV detector is being considered a version with a Micro-Channel Plate (MCP) intensifier, coupled with fiber-optics (ICID).

3.4 Data Rates and Volume

The primary driver of the data rate is the UVCI efficiency in the three channels. In the two EUV lines, the coronal signal is weaker and the instrument efficiency lower than in the visible band. Therefore, longer exposure times will be required for the EUV coronal observations. The countrate for H I and He II Lyman-α emission from a coronal hole (i.e., worst case) has been estimated. If we assume 2 $R_\odot$ as the prime height for coronal observation, the countrate at this height can be used as a fiducial for the data rate estimate. An average exposure time of 600 sec is necessary in order to accumulate a few hundreds EUV counts.

A single image (4096 $\times$ 4096) pxl^2 with 16 bit (b) per pixel takes about 270 Mbit of memory. Assuming that only 50% of the image is used (the rest is occulted disk, extreme corners of the square matrix, and outer corona, i.e., above 3 $R_\odot$, with only a few counts which can be masked "on-chip"), and that a factor of 3 lossless compression can be achieved by using the Rice algorithm, then the image size of a 600s-exposure is about 45 Mbit. This corresponds to a data rate of 0.07 Mbps per detector.

About 150 600s-exposures could be acquired in one day, in one EUV channel. The Visible-light detector can work simultaneously with the H I Lyman-α (about 50% of the time) increasing the total images to 220 per day. Therefore, the data volume accumulated in a 26-day perihelion period (high science rate) is about 260 Gbit. (See Table 1).

Image Compression The data rate and data accumulation per orbit of the SO Spectrometer Package is 0.06 Mbps and 240 Gbit, respectively. Assuming that these resources are split equally among the four instruments of the Spectrometer Package, then a compression factor between 5 and 7 is needed for the UVCI data. A factor 10 is needed to reach about 10 Kbps. This level of compression can be achieved with an acceptable loss of information with schemes such as, for instance, the "Adaptive Discrete Cosine Transform" (ADCT). The ADCT technique is being used in the Large-Angle Spectroscopic Coronagraph (LASCO) on SOHO.

4 Observing Program

The SO orbital scheme offers, for each perihelion passage, three sets of observation periods (ten days each):

1. Maximum Northern latitude.
2. Maximum Southern latitude.
3. Perihelion passage at low differential rotation between SO and Sun (near-heliosynchronous).

Out-of-Ecliptic Observing Programs: The UVCI's observing program is designed to optimize the science return for each of these observing periods. During the two out-of-ecliptic viewing-periods, large-scale observations will be privileged. These type of observations will provide for the first time a global, "synoptic" picture of the solar corona from the advantage points of out-of-ecliptic latitudes. The *Synoptic observing program* is characterized by complete field-of-view coverage at the expenses of spatial resolution with "on-chip" binning, if needed. This program can be selected with different exposures times, with the shorter being used for imaging the inner corona, and the longer the outer corona.

Orbital Period	Observing Program	Time	Description
Out-of-ecliptic (two 10-days periods)	Synoptic	70%	Complete FOV coverage; Low-spatial resolution
	Temporal Resolution	10%	Many short-exposures; Many limited-FOV cov.
	Spatial Resolution	10%	Short-exp. (inner cor.); Long-exp. (outer cor.); Full spatial resolution; Many limited-FOV cov.
	Doppler Dimmimg	10%	Visible & HI Ly-α det's working simultaneously
Near-synchron. (one 10-days period)	Temporal Resolution	30%	
	Spatial Resolution	30%	
	CMEs watch	20%	Very short-exposures; Few limited-FOV cov.
	Doppler Dimmimg	10%	
	Synoptic	10%	
End of perihel. passage	Disk Measurements	few meas.	Coarse disk imaging Vis. & EUV Radiometry

Figure 1: Proposed UVCI observing program during a perihelion passage

Perihelion Observing Programs: During the perihelion passage, the observing program will take advantage of the low differential rotation between SO and Sun. Programs where coronal images are taken with high-temporal cadence, and limited field-of-view coverage, will follow the temporal evolution of coronal structures, such as, for instance, coronal mass ejections (CMEs). The near-heliosynchronous viewing point will reduce the confusing changes of prospective introduced by the solar rotation. Similarly to the *High-temporal resolution* programs, high-spatial resolution, with limited field-of-view coverage, will also be used during the perihelion passage in order to observe fine structures of the corona from the closest viewing-point. Series of *High-Temporal, -Spatial Resolution* programs will be used in sequence in order to cover the entire UVCI's field-of-view.

Special Observing Programs: During both the out-of-ecliptic and near-synchronous periods, special observing programs will also be run. Very high-temporal resolution sequences, covering few, limited FOV will be used in *Watch mode* to catch the onset of CMEs and follow their evolution. Measurements of the solar wind outflow velocity through the *Doppler Dimming* technique require simultaneous obervations with the Visible-light and the H I Lyman-α detectors. This results in a power consumption higher than that in the nominal operational mode (i.e., 35 W). For this reason, the *Doppler Dimming* observing program will be run in close coordination with the other instruments of the SO Spectrometer Package in order to optimize the spacecraft power resources. Another special observing program is the *Disk measurements*. This program will be run a few times, at the end of the perihelion passage for the purposed of coarse disk-imaging and visible-light and EUV radiometric calibration.

The table in Figure 1 gives an example of a possible UVCI observing program during a perihelion passage.

Mission Observing Strategy: An important consideration is that the instrument operations must be highly autonomous. The restrictions placed on the downlink by the near-Sun trajectory (e.g., the need to stow the high gain antenna near perihelion) result in a mission observing strategy that involves the uplink, and on-board storage, of a master schedule with a sequence of observing programs. The programs will be already stored as "embedded sequences" in the UVCI on-board memory. In order to minimize uplink telemetry, the observing master schedule will contain only the time-tagged commands activating the on-board "embedded sequences." Occasionaly, new, or updated, "embedded sequences" will be uploaded. A pre-loaded, default master schedule is executed automatically in the event that no new schedules are loaded.

4.1 Instrument Operation Modes

Seven UVCI operation modes are described below.

1. *Standard Observation Mode* is used for most observations. In this mode, the detectors are on, and the operating voltages are applied. The filter mechanism in configured for the selected channel observation.
2. *Disk Observation Mode* is used for coarse disk imaging and radiometric measurements of the disk intensity in the visible and EUV. The alternative optical path to the the detectors is opened, and filters with high optical density are inserted
3. *Safe Mode* can be selected during flight or during ground testing. This mode is also enabled by instrument safety alarms. Software safety alarms will trigger when limits for instrument pointing and detectors count-rate are exceeded. Finally, UVCI will be this mode, with the entrance aperture door closed, for most of the time of the aphelion orbital period.
4. *Standby Mode* is used for enablig or disabling control to various instrument functions. Detectors are off.
5. *Initialization Mode* is used when booting the flight software from on-board memory.
6. *Pre-operations Mode* enables power but no movement of mechanisms.
7. *Diagnostic Mode* is used to disable all safety alarms and is mainly useful for ground testing.